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Multi-objective optimization of a stand-alone hybrid renewable energy system by using evolutionary algorithms: A review

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ABSTRACT

Hybrid renewable energy system has been introduced as a green and reliable power system for remote areas. There is a steady increase in usage of hybrid renewable energy units and consequently optimization problem solving for this system is a necessity. In recent years, researchers are interested in using multi-objective optimization methods for this issue. Therefore, in the present study, an overview of applied multi-objective methods by using evolutionary algorithms for hybrid renewable energy systems was proposed to help the present and future research works. The result shows that there are a few studies about optimization of many objects in a hybrid system by these algorithms and the most popular applied methods are genetic algorithm and particle swarm optimization.

Contents

1. Introduction 3364
2. Multi-objective optimization 3365
3. Multi-objective optimization methods applied to different HRES 3366
   3.1. PV–battery HRES 3367
   3.2. PV–wind–battery HRES 3367
   3.3. PV–wind–diesel–battery HRES 3367
   3.4. Other HRESs 3368
4. Conclusion 3368
   References 3368

1. Introduction

As the world energy demand will increase up to 53% by 2035 [1], the usage of renewable energy has been steadily increasing over the past few years to help solving acute problems of energy and environmental concerns especially global warming [2,3]. Furthermore, special legislation on energy, which came into effect in 2003, forces energy producers to look at cleaner forms of generating electricity in order to combat global warming caused by green house gases [4] as shown in Fig. 1 [5].

On the other hand, an important decision for governments and companies is whether or not to establish renewable energy systems in a given place, and to decide which renewable energy source or combination of sources is the best choice [6]. Combination of sources to form a single renewable energy system can be called as hybrid renewable energy system (HRES). HRESs are usually more reliable and less costly than other type of renewable systems that rely on a single source of energy [3,7–9]. HRESs use different source of energy and their advantages are: increasing the efficiency, reliability life time of battery bank, reducing the cost of battery bank, longer variations in average wind speed, and about 26–40% saving as compared to only photovoltaic (PV) systems [4]. HRES is becoming popular for remote area power generation applications due to advances in renewable energy technologies and subsequent rise in prices of petroleum products [10]. Most rural areas do not have

Abbreviations: RE, renewable energy; PV, photovoltaic; GA, genetic algorithm; RETs, renewable energy technologies; VRLA, valve regulated lead acid; SOC, state of charge; HRES, hybrid renewable energy system; LP, linear programming; EUE, expected unnerved energy; LCOE, levelized cost of energy; LCE, life cycle emissions; HBMO, honey bee mating optimization; MOEA, multi-objective evolutionary algorithms; MPPT, maximum power point tracking; GHG, green house gases; HBMO, honey bee mating optimization; PSO, particle swarm optimization; EA, evolutionary algorithm; AI, artificial intelligence.

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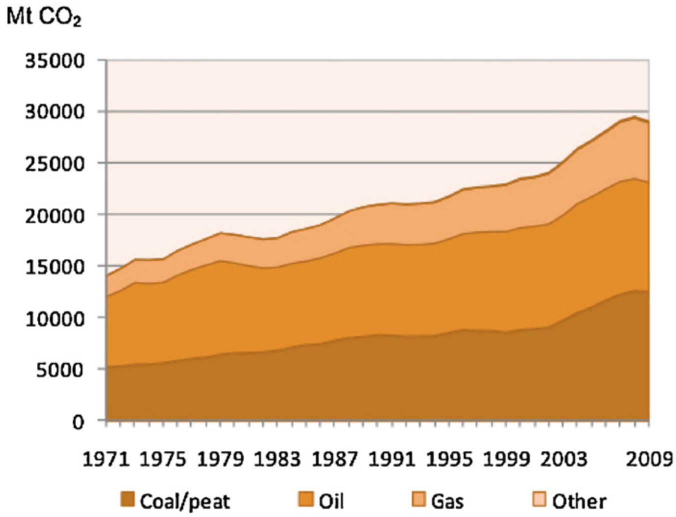

Fig. 1. World CO_2 emissions from fuel combustion.

access to electricity, and to provide electricity in these areas by increasing the scope of the electrical grid is often costly and has challenges [4]. Therefore the HRES is the best choice.

Various aspects and problems must be taken into account when the major discuss is about the optimization of a stand-alone hybrid system [11,12]. Optimizing cost, reliability, design and control, placement and acceptable power quality are some of these problems [13]. In recent research works for optimization of a RE unit, there are an increase in usage of evolutionary computations, due to they are suitable for multi-objective issues by implementing a heuristic algorithm. Researchers in recent years applied multi-objective evolutionary algorithms (MOEA) to solve one of those problems. MOEA, which classified in population based methods [11] are suitable for this problem because they have the ability to attain the global optimum [15].

Although there are many research works about optimization of a HRES [13–25,52], but there are a few works that consider more than one object in optimization problem of a HRES by using evolutionary algorithm (EA) [10,23–27]. This review goes on to offer an overview of latest research advances in multi-objective optimization methods that applied for a HRES.

2. Multi-objective optimization

In this section, adaptability of multi-objective optimization methods with proposed problems will be discussed. Based on previous works, the multi-objective approaches are accurate and real for many complicated optimization problems [28] by considering many conflicting objectives and keep the priority of each one based on their importance [28]. In the last decade, evolutionary approaches have been the primary tools to solve real-world multi-objective problems [28]. On the other sides, there are many shortcomings in studies of single-objective methods, which are formulated as a problem whose goal is to find the “best” solution, which corresponds to the minimum or maximum value of a single objective function that group all different objectives into one [29]. Thus, using multi-objective algorithms allow decision-makers to think about the trade-offs between different benefits of different objects and choose the prior one [29]. Many, or even most, real engineering problems actually do multiple-objectives, such as minimizing cost, maximizing performance, maximizing reliability, etc. These are difficult but realistic problems [6,30]. These methods can provide solutions to increasing complex energy management problems [31].

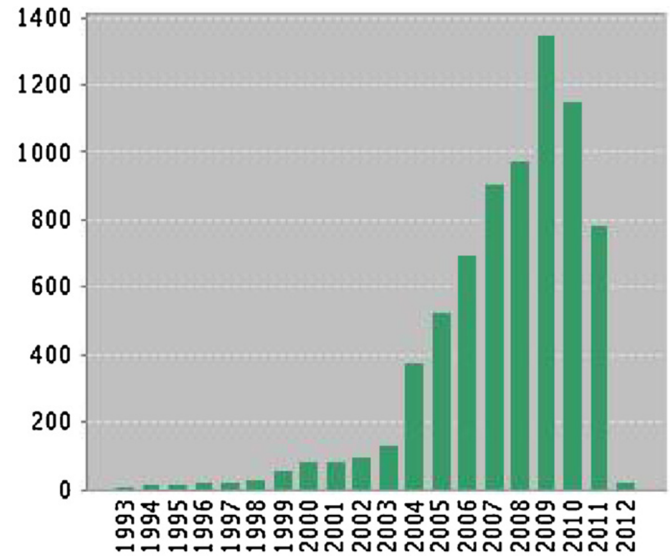

Fig. 2. Published items in recent 20 years.

Taking into account information from the ISI web of knowledge, Fig. 2 shows the published items about multi-objective optimization in a period of 20 years. It can be observed that high number of researchers have interested in this research area.

Although in years 2010 and 2011 less amount of publications are published in this research area, but the large number of citations (Fig. 3) on these years really show the overall interest in the subject.

There are two general approaches to multiple-objective optimization. One is to combine the individual objective functions into a single composite [28]. The second general approach is to determine an entire Pareto optimal solution set or a representative subset [28].

In Pareto based approaches, a decision-maker is considered who wishes to optimize many objectives where the objectives are non-commensurable and the decision-maker has no clear preference of the objectives relative to each other. In this situation a solution is said to be Pareto optimal if it is not dominated by any other solutions in the solution space. A Pareto optimal solution cannot be improved with respect to any objective without worsening at least one objective. The set of all feasible non-dominated solutions in solution space is referred to the Pareto optimal set, and for a given

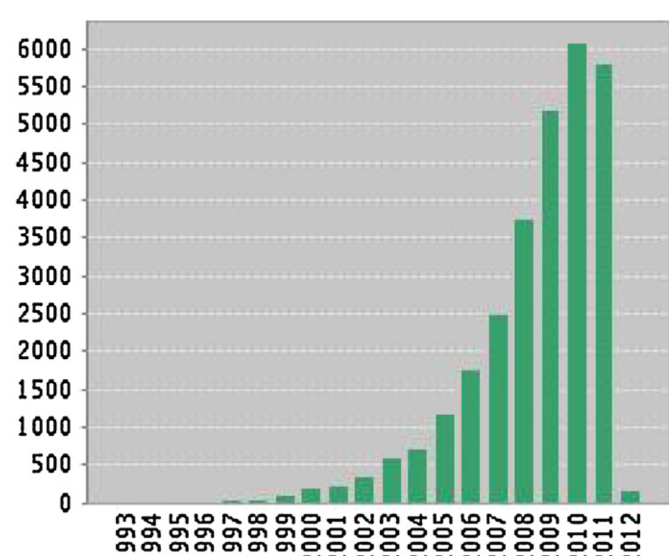

Fig. 3. Citations in recent 20 years.

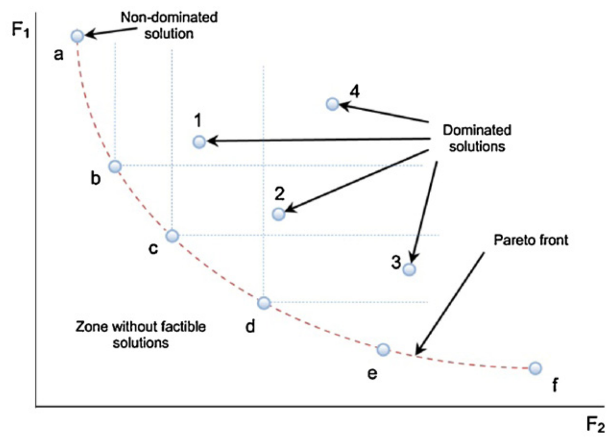

Fig. 4. Pareto front of a MOEA [23].

Pareto optimal set, the corresponding objective function values in the objective space are called the Pareto front. For many problems, the number of Pareto optimal solutions is enormous (perhaps infinite) [28].

The ultimate goal of a multi-objective optimization algorithm is to identify solutions in the Pareto optimal set. However, identifying the entire Pareto optimal set, for many multi-objective problems, is practically impossible due to its size. Therefore, a practical approach to multi-objective optimization is to investigate a set of solutions (the best-known Pareto set) that represents the Pareto optimal set as well as possible. With these concerns in mind, a multi-objective optimization approach should achieve the following three conflicting goals [28]:

1. The best-known Pareto front should be as closed as possible to the true Pareto front. Ideally, the best-known Pareto set should be a subset of the Pareto optimal set.
2. Solutions in the best-known Pareto set should be uniformly distributed and diverse over of the Pareto front in order to provide the decision-maker a true picture of trade-offs.
3. The best-known Pareto front should capture the whole spectrum of the Pareto front. This requires investigating solutions at the extreme ends of the objective function space.

Identifying the Pareto front from a set of points in a multi-objective space is the most important and also the most time-consuming task in multi-objective optimization. Usually, this is done through called no dominated sorting. Fig. 4 shows all mentioned above [23].

Therefore, applications of heuristic approaches, Pareto-based multi-objective optimization and parallel processing are promising research areas in the field of renewable and sustainable energy [6].

3. Multi-objective optimization methods applied to different HRES

This section will explain the proper optimization methods for solving obstacles against of hybrid units. In several papers, many objective methods for solving problems in RE systems are stated and a few of them propose them to be applied in HRES. A review of these methods for HRES from the point of view of placement, sizing, operation, design, planning and control is provided below.

Konak et al. [28] carried out overview and tutorial describing genetic algorithm (GA) developed specifically for problems with multiple objectives. This paper concludes GA is a popular meta-heuristic that is particularly well suited for this class of problems.

The first popular method applied for many objective optimizations of HERS in recent years is GA. GA has been proved to be a good method to solve large scale and combinatorial optimization problem [32]. In [22], Dufo-López and Bernal-Agustín used GAs to optimize a control strategy for a PV–diesel–battery–hydrogen system. In a prior paper [33], they described optimization of the hybrid PV–diesel system using GAs by HOGA software. Masoum [13] improved GA for optimal placement of a hybrid PV–wind system among given candidate locations. In reference [2] an improved GA is developed for achieving the optimization of the hybrid RE system by considering its operation during its lifetime. In recent papers, sizing problem in hybrid systems is discussed more than other problems such as placement, cost, and even design and control strategy. Cinar et al. [34] demonstrated an application of a hybrid model, improving the forward feeding back-propagation model with GA. Kalantar and Mousavi [35] accomplished optimal sizing and economical analysis of the wind–micro turbine–PV–battery hybrid system using GAs for minimizing the annualized cost of system. In another research, Ould Bilal [16] optimized sizing of a hybrid solar–wind–battery system through multi-objective genetic algorithm with two principal aims of the minimization of the annualized cost system and the minimization of the loss of power supply probability. Koutroulis et al. [15] proposed optimal sizing of stand-alone PV–wind generator systems using GAs. Yang [17] recommended an optimal sizing method to optimize the configurations of a hybrid solar–wind system employing battery banks based on a GA. The optimal sizing method was developed to calculate the optimum system configuration that can achieve the customers required loss of power supply probability (LPSP) with a minimum annualized cost of system (ACS). Bourouni et al. [36] presented a new model based on the GAs allowing the generation of several individuals (possible solutions) for coupling small Reverse Osmosis unit to RES.

The second favorite method in recent papers for this problem is particle swarm optimization (PSO). In [37], an evolutionary particle swarm optimization approach was proposed to solve the wind–PV capacity coordination for a time-of-use rate industrial user. Kaviani [14] presented an advanced variation of PSO algorithm for optimal design of a reliable hydrogen-based stand-alone wind–PV generating system with aim of minimization of annualized cost of the hybrid system. Hakimi and Tafreshi [24] demonstrated PSO algorithm that used for optimal sizing of a stand-alone hybrid power system for Kahnouj area in southeast of Iran with aim of minimizing the total costs of the system. Boonbumroong et al. [38] optimized the configuration of a typical AC-coupling stand-alone hybrid power system by PSO to minimize the total cost through the useful life of the system at Chik Island in Thailand. The software used in this work is HOMERpro. Moghaddam [39] presented an expert multi-objective adaptive modified PSO for optimal operation of a typical micro-grid with RE sources accompanied by a back-up micro-turbine–fuel cell–battery hybrid power source with aim to level the power mismatch or to store the surplus of energy when it is needed. In this paper, for improving the optimization process, a hybrid PSO algorithm based on a Chaotic Local Search (CLS) mechanism and a Fuzzy Self Adaptive (FSA) structure was utilized. Avril et al. [27] presented a multi-objective design of hybrid PV–battery based on PSO.

A few researchers exactly focus on optimization of many objects in a RE. Niknam [10] used HBMO algorithm for multi-objective placement of renewable energy resources. Although Niknam's paper can be summarized as optimal sitting and sizing of renewable electricity generators, but it is not for HRES. Brenal [33] applied an EA for the efficient design and control of hybrid systems of electrical energy generation, obtaining good solutions but needing low computational effort. Ban˜os et al. [6] reviewed the current state of the art in computational optimization methods applied to renewable and sustainable energy, and concluded that some researchers

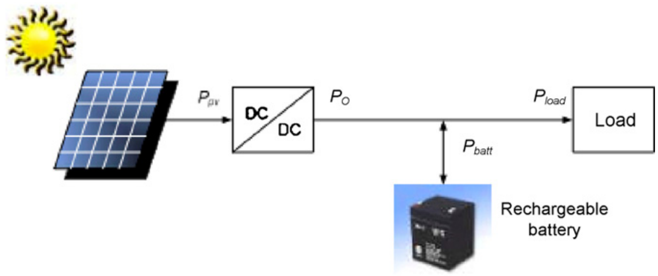

Fig. 5. Block diagram of a conventional PV–battery system.

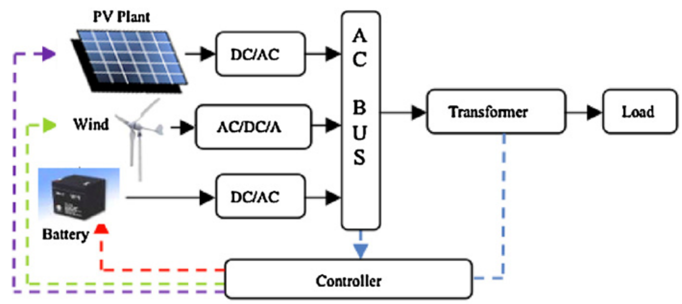

Fig. 6. Block diagram of a conventional PV–wind–battery system.

have solved multi-objective problems related to renewable energy systems using Pareto-optimization techniques. Zhou [25] concentrated on reviewing the current state of research on optimum sizing of stand-alone hybrid solar–wind power generation systems with graphical construction method, probabilistic approach, iterative approach and artificial intelligence method and introduced several software tools for designing of hybrid systems, such as HOMER, HYBRID2, HOGA and HYBRIDS.

Beside all mentioned, some authors [26] work on a triple multi-objective design of isolated hybrid systems which minimizing the total cost throughout the useful life of the installation, pollutant emissions (CO_2) and unmet load by MOEA.

Whereas the stand-alone HRES design and performance depend to location and climate [11,40,49], this paper will discuss optimization of various types of hybrid systems separately.

3.1. PV–battery HRES

Nowadays, the available application area and the installation of PV system are rapidly growing by a number of factors such as global warming, energy security, technology improvements and decreasing costs. In particular, stand-alone PV generation systems are attractive and indispensable electricity source for the security camera devices, streetlights, electric signs and weather observation systems where some of them may be placed in remote or mountainous locations [41].

The energy storage devices are necessary to the stand-alone PV generation system. The battery charging and discharging control with the maximum power of PV array is the key point to increase efficiency of the generation system [42]. A typical stand-alone system, as shown in Fig. 5, incorporates a photovoltaic panel, regulator (DC–DC converter), energy storage system (rechargeable battery), and load [43].

Generally the most common storage technology employed is the valve regulated lead acid (VRLA) battery because of its low cost and wide availability. Photovoltaic panel is not an ideal source for battery charging; the output is unreliable and heavily dependent on weather conditions, therefore an optimum charge/discharge cycle cannot be guaranteed, resulting in a low battery state of charge (SOC). Sizing the battery is related to the cost; in photovoltaic systems the batteries are replaced typically every 3–5 years depending on the application [43,44].

The off-grid or stand-alone PV system incorporates large amounts of battery storage to provide power for a certain number of days (and nights) when sun is not available. The array of solar panels must be large enough to power all energy needs at the site and recharge the batteries at the same time. The aim is to optimize the battery hybrid storage system to reduce the size of the battery and extend the life of the battery by avoiding deep discharge through high currents [43].

Badejani [20] simulated a stand-alone PV-energy storage system in HOMER environment for sizing optimization, which minimizes the system cost. But the proposed stand-alone system is not a HRES; it is a telecom power system. In another paper [6], the potential of artificial intelligence (AI) as a design tool for the optimal sizing of PV–battery systems was explored. Additionally, the advantage of using an AI-based sizing of PV systems is that it provides good optimization, especially in isolated areas, where the weather data are not always available.

In some cases, this type of hybrid system is used for street lighting. Lagorse [18] explained about sizing optimization of a stand-alone street lighting system powered by a hybrid system using fuel cell, PV and battery. He used two optimization algorithms: first the GA to find the approximate global optimum and then a simplex algorithm to enhance the previous result. In another case [45], optimization of the size of a solar thermal electricity plant by means of genetic algorithms is discussed.

3.2. PV–wind–battery HRES

The PV–wind–battery HRES use three power systems, which are each capable of operating in stand-alone operation in order to ensure availability for load demand together. The controller developed for this system monitors the status of availability and connects the load to the available source. Fig. 6 shows the conceptual model of the PV–wind–battery HRES [21].

To improve the performance of the system under different environmental conditions, MPPT of the photovoltaic system and blade angle pitch control of wind turbines were included [20,46]. Mousavi Badejani [20] presented an effective methodology for design and modeling of hybrid wind–photovoltaic systems including their planning and analysis using discrete optimization of cost function and energy balance calculation.

3.3. PV–wind–diesel–battery HRES

Hybrid PV–wind or PV–wind–diesel systems with battery storages have been widely studied in the technical literature [23]. Given that PV and wind systems are still relatively expensive in their installation costs, hybrid systems, which include a diesel generator, often have a lower installation cost than single-type renewable systems [23]. Also, this kind of HRES has been introduced as the most common hybrid system [11].

Saif, Gad Elrab and Kirtley [47] proposed a multi-objective optimization of a PV–wind–diesel–battery HRES. They formulated the problem as a linear programming (LP) model with two objectives: minimizing total cost and minimizing total CO_2 emissions, while capping the expected unnerved energy (EUE).

Dufo-López et al. [23] described an application of the strength Pareto EA to the multi-objective optimization of a stand-alone PV–wind–diesel system with battery storages. The objectives to be minimized are the levelized cost of energy (LCOE) and the equivalent CO_2 life cycle emissions (LCE).

Belfkira [21] evaluated a methodology of sizing optimization of a stand-alone hybrid wind–PV–diesel–battery energy system with

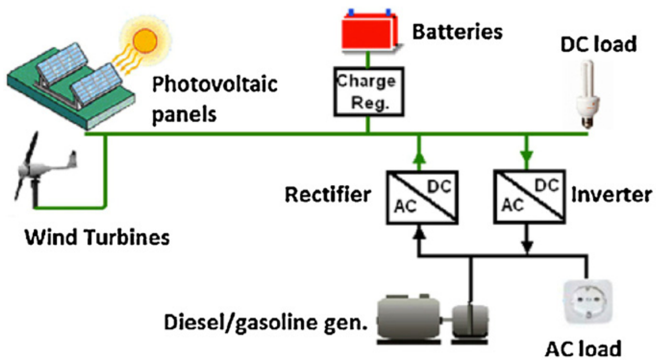

Fig. 7. Block diagram of a conventional PV–wind–diesel–battery system [23].

aim of minimizing total cost of the system while guaranteeing the availability of the energy. Fig. 7 shows the Block diagram of a conventional PV–wind–diesel–battery system.

3.4. Other HRESs

The overall RE system performance and design are very sensitive to local weather conditions [48]. Thus it is very essential to propose a certain HRES for a definite location.

Kenfack [49] presented size optimization model for micro hydro-PV–diesel–battery hybrid system in a village in Cameroon. Bakos [50] carried out operation of a hybrid wind-hydro power system aiming at producing low cost electricity in the island of Ikaria in Greece. In [51] Dalton analyzed PV, wind, battery, diesel system for subtropical coastal area of Queensland, Australia.

4. Conclusion

This paper provides an overview of the latest research works about the use of multi-optimization algorithms for placement, sizing, design, planning and control problems in the field of renewable and sustainable energy. The first finding of this review is that although there are a large number of optimization methods for RE, however a few of them have discussed around multi-objective optimization of stand-alone hybrid renewable energy system by using heuristic algorithm.

The second finding is indication of a fast and significance growth of using MOEA for engineering problems. As we mentioned the HRES design is very sensitive to local conditions, thus, there is a promising research area in finding solution for many objective optimizations by MOEA in a special place. Future research can be focused on application of a specific evolutionary algorithm for a multi-objective optimization of a HRES in a proposed area.

Among various EAs, this review concludes that the using of GA and PSO are the most useful and promising methods in HRES design. These two methods are heuristic algorithms, which gain global optima, and this is the important reason for applying them.

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